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NEW AND OLD ACCELERATORS: WHAT CAN THEY DO FOR ASTROPHYSICS?*

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ABSTRACT

The quantum numbers and energy spectrum of high energy accelerators and storage rings are described, along with some ways they may contribute to astrophysical issues. Some emphasis is given to the role of relativistic heavy-ion colliders in possibly providing laboratory samples of quark-gluon plasma.

I. INTRODUCTORY APOLOGIES

This talk, given by an amateur in astrophysical issues, must be regarded as an incomplete and subjective look at this subject. Emphasis will be given, not surprisingly, on topics of particular interest to this speaker. Little apology need be given for some of the omitted topics (e.g. monopoles, proton decay, neutrino masses and oscillations, and axions, standard and/or invisible), which are well covered in other talks[1] given at this workshop.

The material which will be discussed is organized from low energy to high (or in big-bang terms, from late to early times). We shall first, for those unfamiliar with the acronymics of high energy accelerators, briefly review the experimental facilities now available and planned for the future. In Section III we discuss phenomena at "late" times or low energies (<< 100MeV). Section IV concentrates on the hadronization epoch (100 MeV - 1 GeV), where study of relativistic heavy-ion collisions may be relevant. Section V deals with the bread-and-butter energy scales (1 GeV - 10 TeV) of the high energy physicist, with the concluding section mentioning the region beyond.

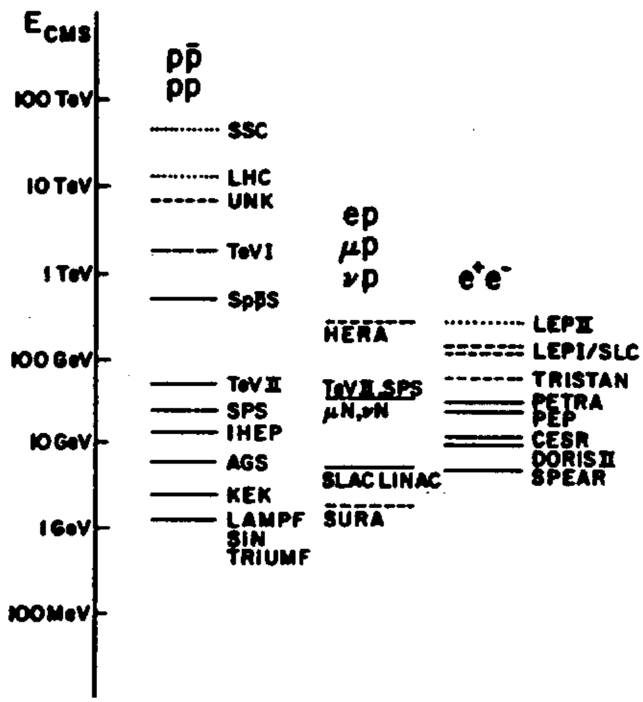

Figure 1: Energy-level diagram for particle accelerators.

II. THE SPECTRUM OF ACCELERATORS AND STORAGE RINGS

We here review the accelerators and storage rings existing, under construction, and planned for the future, which might contribute new information for the astrophysicist. These are shown in Fig. 1 in an energy-level diagram, as a function of their quantum numbers. One may collide hadrons with hadrons, hadrons with leptons, or leptons with leptons. The acronyms shown in Fig. 1 mean the following:

A) Hadron-Hadron Collisions:

LAMPF(Los Alamos), SIN(Zurich), TRIUMF(Vancouver): "Medium-energy" facilities with proton beams under 1 GeV. Especially useful for high energy physicists are the neutrino physics and rare decays of pion and (after proposed upgrades?) kaon.

KEK,AGS: 8 and 24 GeV proton synchrotrons in Tsukuba and Brookhaven, respectively.

IHEP: 70 GeV proton synchrotron in USSR.

SPS,TeV II: 400 and 1000 GeV synchrotrons operating at CERN (Geneva) and Fermilab respectively. Diversity of approach for investigations of collisions with center-of-mass energies of 20 - 40 GeV.

$Sp\bar{p}S$: 270 × 270 GeV proton-antiproton collider operating at CERN; site of $W^{\pm}$, Z^{0} weak gauge boson discovery.

Tev I: 1 TeV × 1 TeV proton-antiproton collider under construction at Fermilab, commissioning in 1986-1987.

UNK: Large proton synchrotron under construction in Serpukhov, USSR. 400 GeV protons onto fixed targets available no earlier than late 1980's; ultimately 3 TeV × 3 TeV proton-proton (or antiproton?) collisions might be provided at some uncertain date in the 1990's.

LHC: Possible proton-proton or proton-antiproton collider at CERN in LEP enclosure (see electron-positron listing); energy in the range of 5 × 5 TeV to 9 × 9 TeV; commissioning no earlier than 1994±2.

SSC: Possible 20 × 20 TeV proton-proton or proton-antiproton collider in US; highest priority of future US high-energy physics program.

B) Lepton-Hadron Collisions:

SURA: 4 GeV electron accelerator to be built in Newport News, Va.

SLAC: 20 GeV electron linac at Stanford, Ca.

SPS,TeV II: 200 - 600 GeV muon and neutrino secondary beams onto fixed targets.

HERA: 30×800 GeV electron-proton collider under construction at DESY (Hamburg, Germany); commissioning in 1989.

C) Electron-Positron Collisions:

SPEAR: 3×3 GeV electron-positron collider storage ring; site of Ψ and charmed quark discoveries; excellent machine for study of hadrons containing charmed quarks.

DORIS II,CESR: 5×5 GeV and 8×8 GeV electron-positron colliders at DESY and Cornell; excellent machines for study of hadrons containing bottom quarks.

PEP, PETRA: 14×14 GeV and 23×23 GeV electron-positron colliders.

TRISTAN: 30×30 GeV electron-positron collider under construction in Tsukuba, Japan; commissioning in 1986.

SLC, LEP I: 50×50 GeV electron-positron colliders under construction. SLC (at SLAC) uses a new "single-pass" technology employing the linear accelerator; LEP I (at CERN) is a "conventional" circular ring 26 km in circumference. SLC commissioning should occur in 1986; LEP I in 1988.

LEP II: Upgrade of the CERN collider to 70 - 100 GeV per beam.

In assessing the relative capability of the colliders, one must take into account the fact that at high energies a single proton should be regarded as a "beam" of its constituent quarks and gluons, and that seldom does more than one third of the proton momentum reside in a single constituent. Thus an electron-positron collider of center-of-mass-energy E_e should be compared with hadron-hadron colliders of energy $E_p \sim (3\text{-}5)E_e$.

III. LOW ENERGIES AND LATE TIMES

Neutrino physics and astrophysics are clearly intertwined but, as promised, little will be said here. Perhaps the next big step will be the resolution to the He^3 β-decay spectrum puzzle in the next year or two.

A direct contribution of accelerators will be the upcoming neutrino count from measurement of the width of the Z^o at SLC and LEP II (with $Sp\bar{p}s$ and TeV I having an outside chance, too). The total width of Z^o (of order 3 GeV) receives contributions from the decay $Z^o \to T_n\bar{T}_n$. Assuming any new T_n to have "standard" weak coupling, the change in width $d\Gamma/dn$ with respect to the number n of neutrinos is 180 MeV per neutrino. The total width of ~3 GeV is measurable in e^+e^- annihilation by scanning the line shape, i.e. measuring the yield of Z^o's as function of beam energy. An alternative method uses radiative production, $e^+e^- \to Z^o+\gamma$, and compares $Z^o \to \nu_n\bar{\nu}_n$ (in this case directly observable) with $Z^o \to e^+e^-$ and/or $Z^o \to \mu^+\mu^-$. At present, the limit from $Sp\bar{p}S$ on the number of neutrinos is somewhere around a dozen, scarcely of interest yet to astrophysicists.

One of the most interesting "late-time" astrophysical issues impacting particle-physics is the "dark-matter" problem. If mundane explanations do not suffice, some extension of the presently known low-mass particle spectrum seems to be required. Massive neutrinos are one option. Supersymmetric particles (photinos, sneutrinos?) are another. Axion-like entities are yet another. Accelerator searches can be (and have been) made in a variety of ways. Decay of mesons (e.g. $K^+ \to X^0+\pi^+$, $\Psi \to X^0+\gamma$, $\Upsilon \to X^0+\gamma$) have been used to search for candidate bosons. Here low energy facilities, e.g. LAMPF, SIN, TRIUMPF, SPEAR, AGS, are especially valuable. Collider events with large missing transverse momentum (relative to the beam directions) may signal production of exotic light neutral particles if no conventional explanations suffice. For example, one search method for photinos $\tilde{\gamma}$ uses the process $e^+e^- \to \tilde{\gamma}\tilde{\gamma}+\gamma$, hopefully background-free when the photon has large transverse momentum and the center-of-mass energy is large. The $Sp\bar{p}S$ "zoo events", of which we speak later, are characterized by large missing transverse energy, and likewise invite speculations on new-particle production. Assuming, as appears reasonable, the detectors to be efficient in capturing all other forms of transverse energy, the balance must either be provided by neutrinos (e.g. by Z^0 production followed by $Z^0 \to \nu\bar{\nu}$) or else by some unknown neutral long-lived penetrating particle. Supersymmetry aficionados are now active in trying to interpret these events, but it is probably premature. The next $Sp\bar{p}S$ running period should clarify a presently murky experimental situation.

Beam-dump experiments are another useful way of looking for long-lived neutral penetrating particles. A variety of such experiments have been done with hadron beams at LAMPF, SIN, AGS, PS, SPS, and Fermilab. No convincing signals have been seen, and only limits on parameters for axions, heavy neutrinos, etc. exist. A somewhat typical experiment on these lines was done at SLAC. Since I was a participant in that one, I will dwell briefly on it as a prototype of such experiments. As shown in Fig. 2, 30 Coulombs of SLAC 20 GeV electrons were dumped in a large tank of water, just upstream of 200 meters of natural earth shielding. 400 meters downstream, an electromagnetic shower counter of good angular resolution was placed, where it could detect any decay products produced in

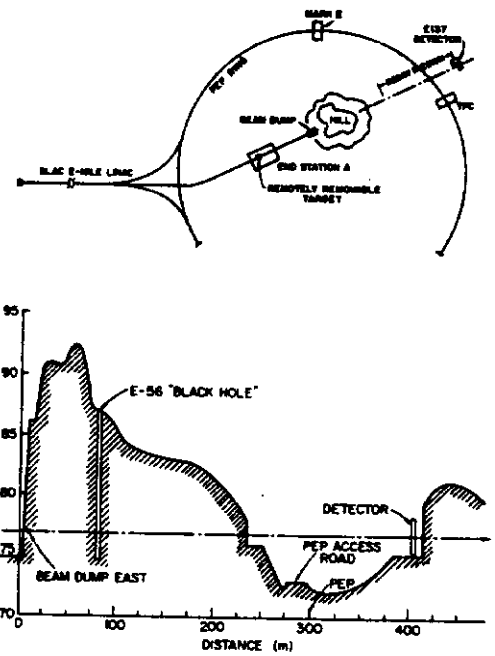

Figure 2: Beam dump experiment E137 carried out at SLAC.

the 200 meters of air upstream of the detector. For example, an axion-like entity X could be produced by the Primakoff mechanism (γ+ coulomb field → X) and then decay back into $\gamma\gamma$. Nothing was seen, and a preliminary lower limit (95% confidence level) for the product of mass and lifetime of 0.8 keV-sec was obtained[2].

IV. THE HADRONIZATION EPOCH

In the very early universe, the appropriate description must be in terms of a plasma of quarks, gluons, and leptons; the densities are simply too high to imagine individual hadrons as indentifiable. Much later this system must turn into hadrons (plus leptons), essentially a dilute gas of pions, with a small contamination of baryons. The transition between these two phases is expected to occur at a temperature of about 200 MeV. This is an issue of interest not only to astrophysicists, but also to lattice gauge theorists, who presume to have - or soon to have - calculational tools adequate to map out the equation of state of hadronic matter. Schematically this equation of state is shown in Fig. 3. At low and high temperature, Stefan and Boltzmann rule. However the large number of internal degrees of freedom (spin, color, etc.) for quarks and gluons outnumber the three for pions by an order of magnitude. Every indication from lattice calculations[3] is that the transition is abrupt, perhaps first-order with a latent heat $\gtrsim$ 1 GeV/fm^3. There may even be two phase transitions, one associated with deconfinement, the other with restoration of spontaneously broken chiral symmetry. This option is at present slightly disfavored, but remains an open question.

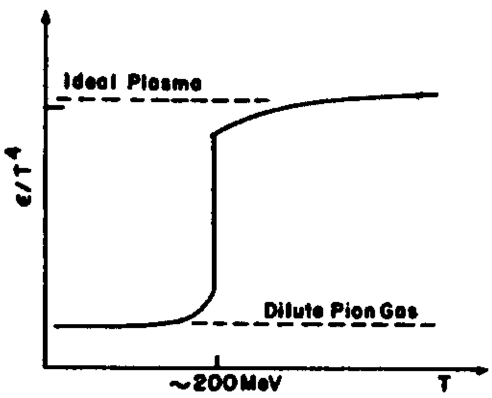

Figure 3: Equation of state of hadronic matter.

Location of the transition temperature experimentally, along with good theoretical calculations, would allow a very good measurement of the strong coupling constant α_s or, better, the QCD scale factor Λ. Thus, for this as well as many other reasons, there is growing interest in trying to observe experimentally the quark-gluon plasma. The opportunity may exist in collisions of relativistic heavy ions. At sufficiently high energy, as viewed in the center-of-mass frame, the incident nuclei (say U; 14 fm diameter) are Lorentz-contracted to a thickness much less than 1 fm. After they collide, the collision products, be they quarks, pions, gluons or something else, are (by causality) confined within the planes of outgoing excited nuclear matter, which in this frame recede at the speed of light. It is reasonable (but not at all proven) that these collision products equilibrate rapidly (ct $\lesssim$ 1 fm??) and even more reasonable that the initial energy density is $\sim$ 1-5 GeV/fm^3, corresponding to quark-gluon plasma above the phase transition (but not by an enormous amount; the temperature is ~ 200-300 MeV). Indeed a direct estimate from observed heavy-ion cosmic ray events tends to corroborate the theoretical estimates of initial energy density.

The geometry of the expansion phase appears to be quite simple. At sufficiently high collision energy the plasma within the receding planes undergoes (to reasonable approximation) a homogeneous one-dimensional longitudinal expansion[4]. That is, a fluid element in the midplane remains at rest, while one halfway between the midplane and the boundary plane moves at half the speed of light, etc. Thus, except for the one-dimensionality of the expansion, the conditions may indeed be quite similar to those which existed in the first three microseconds. In the case of heavy-ion collisions, this state of affairs cannot last very long. The news that the nuclei are finite is transmitted from the edge inward by a rarefaction front traveling at the velocity of sound in the plasma.

The central problem in any future experimental program in relativistic ion-ion collisions is to find connections between the properties of the 10^3 - 10^4 observed collision products, produced in general at late times, with the purported plasma extant (if at all) at early times. Proposed ideas include study of fluctuations and correlations in multiplicity density, composition, transverse momenta, etc., which might be correlated with bulk fluctuations (bubble formation? shocks?) occurring during the phase transition. Another attack is observation of direct photons and/or dileptons produced by the plasma during the initial hot phase. No signature looks supremely clean, and even with more work (sure to come) it will be a tough battle. My own prejudice is that if ion-ion collisions do turn out to reveal to us the existence and properties of quark-gluon plasma, we probably will not anticipate in advance the mechanism of revelation. It may be like neutron stars: theorists knew everything about them in advance - except how to find them. And, despite the fact that everyone is convinced that pulsars are indeed neutron stars, to this day the pulsar mechanism is not well understood.

The experimental prospects for a highly relativistic heavy-ion experimental program are reasonably bright. The first step will be acceleration of ions up to oxygen in the SPS at momenta of 200 GeV/nucleon. Brookhaven is building a transfer line from its Van de Graaf to the AGS, and with addition of a new booster ring ($\lesssim$ 4-5 years) will be able to accelerate the heaviest ions through the AGS. In the longer run, there is a rather detailed proposal to build a relativistic heavy-ion collider ($\lesssim$ 100 GeV/nucleon; $\lesssim$ 6 years) in the CBA tunnel. This facility would be of sufficient energy to attain the clean geometry for plasma production which we described.

V. HIGH ENERGY AND HIGH MASS SCALES/EARLY TIMES

The present theoretical perspective on dynamics above the strong interaction scale emphasizes the restoration of symmetries. As the energy scale increases, the symmetry of the vacuum state, broken at low energy scales, is expected to increase. The first such transition beyond the hadron-to-quark/gluon transition apparently occurs at the electroweak scale of ~100-200 GeV. The estimated[5] standard-model transition temperature is 425 GeV. At energies large compared to this scale, the SU(2) × U(1) symmetry of the electroweak theory is expected to be fully restored. The agreement of the measured W and Z masses with the predictions greatly strengthen confidence that this expectation is correct.

Beyond this scale lies speculation. Proposals for extra tiers of symmetry restoration at higher mass scales come and go with the seasons: "extended technicolor", restoration of global supersymmetry, restoration of left-right symmetry and/or CP invariance, and upward toward grand unification scales.

The phase transitions associated with these conjectured mechanisms may be of the most direct concern to the astrophysicist. To the particle physicist it is the extra particles as well as, perhaps, the breakdown of conservation laws, as in the case of proton decay. This feature might express itself in other ways (lepton nonconservation) and invites scrutiny of conservation laws at all energy scales.

The search phenomena high on the agenda for experimentalists includes the following incomplete list:

1. <u>The Standard Higgs Boson</u>:
Something like this particle <u>must</u> exist; the orthodox standard model predicts everything about it except its mass. The search technique depends a great deal on that parameter[6]. If the Higgs mass is less than about 40 GeV, the method of choice is the process $Z^o \to e^+e^-h$ or $Z^o \to \mu^+\mu^-h$, available at SLC and LEP I. For the 40 to 100 GeV range, LEP II may see it via the related process $e^+e^- \to Z^oh$, with $Z^o \to e^+e^-$ or $Z^o \to \mu^+\mu^-$. Between 170 GeV and 500 GeV, hadron-hadron colliders such as SSC are best. One uses the gluon component within the energetic proton and resonantly makes the Higgs h in a gluon-gluon "fusion": $gg \to h$; the Higgs boson then decays into W^+W^- or Z^oZ^o, which is a hopefully observable final state. The interval between 100 and 170 GeV is awkward; one needs luck or an e^+e^- collider of energy considerably beyond LEP II. The interval above 500 GeV is fraught with background problems; however the mass of h is bounded above by quite general arguments; the limit is around 1 TeV.

2. <u>Flavor Changing Decays</u>:
Rare K decays such as $K \to \mu e$, $K \to \pi\mu e$, etc. probe very high symmetry-restoration(?) scales, and limits on these are well worth pushing further. Searches for rare decays of hadrons containing c and b quarks should also be carried out. The b quark in particular seems to have a surprisingly long lifetime ($\sim 10^{-12}$sec) and thus the branching fraction for crazy rare decays may be especially enhanced. The experiments can be done at e^+e^- machines such as SPEAR, CESR, and DORIS, as well as in the TeV II fixed target program. Also, one should not ignore the possibility of rare Z^o decays (how about $Z^o \to \Upsilon\mu e$?), given that SLC and LEP I may give us more than a million Z's per year.

3. <u>Right-handed Weak Currents</u>:
Here HERA will make important contributions. Positive evidence could well herald a phase transition associated with parity restoration.

4. <u>Compositeness Test for Quarks And Leptons:</u>
These tests (TeV I, SSC, LEP II) could indicate a phase transition to preons similar to the strong interaction transition from hadrons to quark-gluon plasma. Mass scales of up to 30 TeV appear attainable at the SSC.

5. <u>Generic Axions:</u>
Symmetry breaking at high mass scales might provide pseudo-Nambu-Goldstone bosons. A Fermilab experiment (E-635) proposes to search for $X \rightarrow \mu^+\mu^-$ in a range of parameter space which, while small, is exquisitely sensitive to mass scales up to 10^4 TeV (if m_X is $\lesssim 1$ GeV).

These items have in part been listed because they exhibit sensitivity to phenomena at mass scales beyond what is directly available from the accelerator or storage ring. There will be of course the direct searches for generic new phenomena, such as discovery of new quarks, leptons, or gauge bosons. The big three concepts of theoretical speculation are[6]

Technicolor
Compositeness
Supersymmetry

They all imply proliferation of degrees of freedom - many new particles. The main technique of the future, just emergent now at PEP, PETRA, and $Sp\bar{p}S$, is multijet spectroscopy. A quark or gluon is now "seen" as a collimated jet of hadrons directed in the original direction of the parent quark or gluon. These are becoming "tracks" just about as well resolved as the cloud-chamber tracks of hadrons in the old days. The first such jets, back-to-back, were seen at SPEAR via the process $e^+e^- \rightarrow q\bar{q}$, followed by 3-jet $e^+e^- \rightarrow qqg$ events at PETRA. Spectacular 2-jet events $(q\bar{q},qg,gg) \rightarrow (q\bar{q},qg,gg)$ have been seen at the $Sp\bar{p}S$ with center-of-mass energies of over 200 GeV (out of the total 540 available). Multijet events are seen also. Very heavy particles which decay into quarks and/or gluons will contribute multijet final states. (For example $W,Z \rightarrow q\bar{q}$; regrettably these are swamped by backgrounds from the aforementioned scattering processes). An interesting class of "zoo" events from the $Sp\bar{p}S$ UA1 and UA2 experiments have been seen. They are characterized in part by large amounts of escaping transverse momentum, by a large amount of transverse energy (150-200 GeV) and often by presence of a charged lepton. As mentioned before, the missing transverse momentum, if not contributed by neutrinos, would be indicative of production of some kind of long lived neutral penetrating particle (photino? goldstino? sneutrino? axion?). Supersymmetry enthusiasts and other theorists are becoming active, but it is too early to conclude anything. Much more needs to be understood about multijet background processes, and larger samples need to be acquired. Nevertheless, at TeV I and higher energy hadron colliders, it seems certain that the reconstruction of multijet systems will become a routine technique and a powerful avenue toward new-particle discoveries in the 100-1000 GeV mass range.

VI. SUPERHIGH MASS SCALES/THE VERY EARLY UNIVERSE

Prospects for probing GUT mass scales ($10^{15\pm5}$GeV) clearly lie beyond accelerator physics. There is the nucleon decay program and the search for $n\bar{n}$ oscillations (much more speculative), searches for rare superheavy stable relics in terrestrial (or other) matter and the searches for monopoles. Were the monopole search successful, the use of GUT monopole-antimonopole annihilation would provide the ultimate high-energy physics experiment. If one had one SU(5) GUT monopole and one antimonopole and could bring them together to annihilate (nontrivial but thinkable), then the single annihilation could produce several SU(5) X and Y bosons, which could decay into observable, indeed lethal, hadron jets and leptons of energy 10^{14}-10^{15} GeV. A single event would be a radiation hazard. While far out, maybe this at least indicates that high energy experimental physics is a very long way from becoming a sterile discipline.

REFERENCES

[1] See for example, J. Preskill (monopoles), P. Langacker (proton decay), F. Sciulli (neutrinos), and P. Sikivie (axions); these proceedings.

[2] A preliminary report has been made by me at the Fourth Moriond Workshop on Massive Neutrinos, proceedings to be published; cf. Fermilab preprint FERMILAB-Conf-84/33-T.

[3] For a review, see the report of M. Jacob and J. Tran Than Van, Phys. Rep. **88** (1982).

[4] J. Bjorken, Phys. Rev. D**27**, 140 (1983).

[5] A. Linde, Rept. Prog. Phys. **42**, 389 (1979).

[6] E. Eichten, I. Hincheliffe, K. Lane, and C. Quigg, Revs. Mod. Phys. **56**, 579 (1984).